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Special sessions on MTI, Oral Presentation.

Multispectral Thermal Imager Mission Overview.

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ABSTRACT

The Multispectral Thermal Imager (MTI) is a research and development project sponsored by the Department of Energy and executed by Sandia and Los Alamos National Laboratories and the Savannah River Technology Center. Other participants include the U. S. Air Force, universities, and many industrial partners. The MTI mission is to demonstrate the efficacy of highly accurate multispectral imaging for passive characterization of industrial facilities and related environmental impacts from space. MTI provides simultaneous data for atmospheric characterization at high spatial resolution. Additionally, MTI has applications to environmental monitoring and other civilian applications. The mission is based in end-to-end modeling of targets, signatures, atmospheric effects, the space sensor, and analysis techniques to form a balanced, self-consistent mission. The MTI satellite nears completion, and is scheduled for launch in late 1999. This paper describes the MTI mission, development of desired system attributes, some trade studies, schedule, and overall plans for data acquisition and analysis. This effort drives the sophisticated payload and advanced calibration systems, which are the overall subject of the first session at this conference, as well as the data processing and some of the analysis tools that will be described in the second segment.

Keywords: Modeling, Analysis, System design, Multispectral Imaging, Calibration, Satellite, Space-borne Imaging Spectroscopy.

1. INTRODUCTION

Mankind has a long history of observing parts of the planet Earth, with improved capabilities emerging over the ages. Starting in 1965, NASA initiated the Earth Resources Survey (ERS) Program to develop methods for remote sensing of the Earth from space[1]. The Department of Agriculture joined in that program with studies of applications in geology, hydrology, geography, and cartography. The first Earth remote sensing satellite was ERTS-1, launched by NASA in 1972. A fine review of the status of the field as of 1992 is found in a special issue of Remote Sensing of the Environment[2]. Since that time, more government agencies have entered the field, and interest in earth remote sensing by the commercial sector is building rapidly. An excellent starting point for summaries of Earth observing spacecraft and instruments, sponsored by many organizations, is at[3]: http://www.earth.nasa.gov/missions/spacecraft.html.

The US Department of Energy (DOE) is among the agencies interested in furthering remote sensing of the Earth. "The Department of Energy's Laboratories help support American leadership in science and technology", to ensure the energy security of the Nation, and to contribute to other national security issues[4]. A timely example of DOE interests is in the area of Global Climate, where the purpose of current research is[5] to: "understand the factors affecting the Earth's radiant-energy balance; predict global and regional climate change caused by increasing atmospheric concentrations of greenhouse gases; quantify sources of energy-related greenhouse gases, especially carbon dioxide; and improve the scientific basis for assessing the potential ecological, social, and economic consequences of human-caused climate change and the benefits and costs of responses to these consequences." The Energy Information Administration, the independent statistical and analytical agency within the U.S. Department of Energy, maintains a careful watch over energy use around the world, requiring data from a plethora of sources[6].

The Department of Energy's Mission clearly benefits from space-based imaging spectrometry, but some years ago, a review of existing and planned instrumentation showed that the match of these assets to DOE interests left a significant gap. Thus the DOE sponsored the Multispectral Thermal Imager program, which is jointly executed by Sandia National Laboratories, Los Alamos National Laboratory, and the Savannah River Technology Center, in collaboration with the U.S. Air Force and many industrial partners.

2. MISSION DESCRIPTION

The MTI mission is to demonstrate the efficacy of highly accurate multispectral and thermal imaging for passive characterization of industrial facilities and related environmental impacts from space. The MTI goal is to compare the remotely sensed information from the satellite instrument to information available directly at the cooperative sites being observed. In this role, MTI is a technology demonstration experiment, and is designed to observe a very limited number of selected sites per day, with modest spatial coverage and spatial resolution. Assuming that MTI indeed advances the state of the art in remote sensing, we anticipate a transition of some of our system attributes to operational systems such as Landsat and perhaps commercial enterprises.

Our measurement strategy[7] is centered on physics-based end-to-end modeling and analysis. Thus, with reference to Figure 1, we start with a ground scene, which may be from previous observations, or which may be a modeled scene. We generate signatures, and propagate those through the atmosphere to a model of the prototype sensor. Through modeling of the putative sensor attributes, we develop a simulated data stream, which is then used as input to analysis codes. We explicitly include a calibration loop, which lets us balance the uncertainties in the rest of the measurement system with those in the calibration. The products of the analyses are then compared to the most critical attributes of the beginning scene to judge the efficacy of the measurement strategy. A more detailed description of the application of the end-to-end modeling strategy is found in a recent paper[8].

Immediate lessons from examination of the end-to-end models include the fact that the atmosphere contributes considerably to modifying the ground-based signatures, through absorption, scattering, and emission (so-called path radiance). For well-mixed atmospheric constituents we can compensate for these effects; however, aerosols, water vapor, and clouds are highly variable both temporally and spatially. This is easily seen for visible clouds, but also applies to subvisual cirrus[9] which, being patchy and cold, plays havoc with temperature measurements. The spatial variability of water vapor has recently been measured down to scales of meters using three-dimensional scanning of Raman LIDAR[10] identifying structures at scales of several meters even over nominally uniform targets such as the Pacific Ocean. Similar spatial scans of backscatter LIDARs[11] show small-scale spatial variability of aerosols. Temporal variability is easily documented from data obtained at the DOE's Atmospheric Radiation Measurement (ARM) sites[12] and, at lesser quality from weather stations around the world. Based on these observations and modeling, it is insufficient to rely on compensating for the atmosphere on the basis of data from assets other than the MTI satellite itself. Thus MTI has the ability to measure atmospheric water vapor, aerosols, and clouds down to subvisual Cirrus based on techniques pioneered by the AVIRIS airborne sensor[13].

With the ability to compensate for the atmosphere, the next performance-limiting attribute of a multi-spectral sensor becomes the radiometric calibration. Again, with reference to developing a self-consistent measurement strategy, one needs to balance the calibration against uncertainties in the rest of the measurement scenario. The calibration requirements resulting from these considerations then translate to requirements for NIST-traceable calibration standards, pre-launch calibrations, on-board calibration maintenance, and vicarious calibrations on orbit. As we shall see, the calibration systems for MTI stretch the state of the art for calibrations of satellite-borne sensors.

Thus the very top-level requirements for this technology demonstration are:

1. Demonstrate the efficacy of multispectral remote sensing for DOE interests;
2. Incorporate on-board measurements allowing atmospheric compensation;
3. Incorporate advanced radiometric calibrations;
4. Develop and validate physics-based end-to-end modeling and analysis;
5. Make the results available for potential transition to other systems.

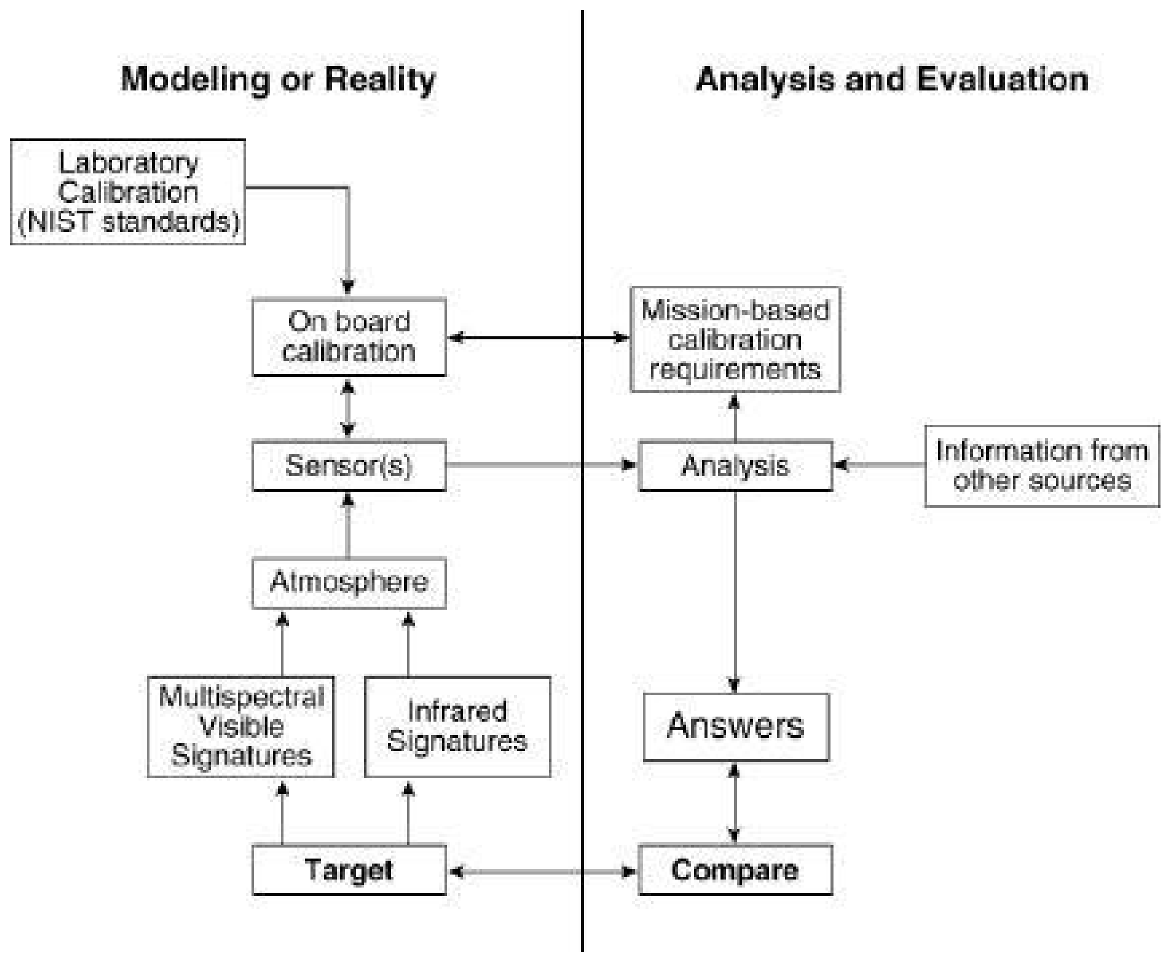

Figure 1: End-to-end model outline.

3. REQUIREMENTS DEFINITION

We present a qualitative discussion, which will illustrate the process by which we derived the actual requirements for MTI. Quantitative evaluations were, in fact, applied to obtain the final set of requirements: we omit these details in the interest of time and space. Further, we conducted a number of trade studies to limit the cost of the system, and to ensure a set of self-consistent specifications.

We begin with spatial resolution, since it determines the size of the optical system aperture, which, in turn, is a strong driver of the size and mass of the full satellite[14]. Ideally, one wishes the best spatial resolution that is affordable, to access the smallest target features of interest. For the MTI mission, we were limited to 20 meter Ground Sampling Distance (GSD) for the longest wavelengths of interest at the peak of the Planck curve in the Long wave Infrared (LWIR). This allows access to a sufficient number of interesting sites, and translates to an optical aperture of 0.36 meters from a nominal 500-km orbit altitude. We note that this 0.36-m aperture, if used in a diffraction-limited telescope, would permit a 2-meter diffraction limit at visible light wavelengths.

We determined the spatial coverage by a trade between coverage of large areas, the pointing capability of the satellite, and the need for a larger number of detectors and concomitant electronics. The MTI satellite is designed to access large industrial and DOE sites, such as segments of the 43 square miles of the Los Alamos National Laboratory and the approximately 310 square miles of the DOE's Savannah River Site. Targets of interest within these sites are generally well dispersed, leading to a compromise swath width of 20 km (but see later for results of a trade study). The costs of pointing the satellite increase sharply for better accuracies, with a documented break point in the cost – performance trade space at a few kilometers. We easily derive the number of detectors (pixels) from spatial resolution, swath width and length, satellite pointing, and affordable data rate. The final trades in this area led to 5-m GSDs for the four shortest wavelength visible bands, and 20-m GSD for the other eleven bands, with a swath width of 12 km., and 98 % confidence of having a 2 x 2 km target in the field of view on any particular acquisition. We set the nominal target length at 12 km, though this can be easily extended with the chosen optical system.

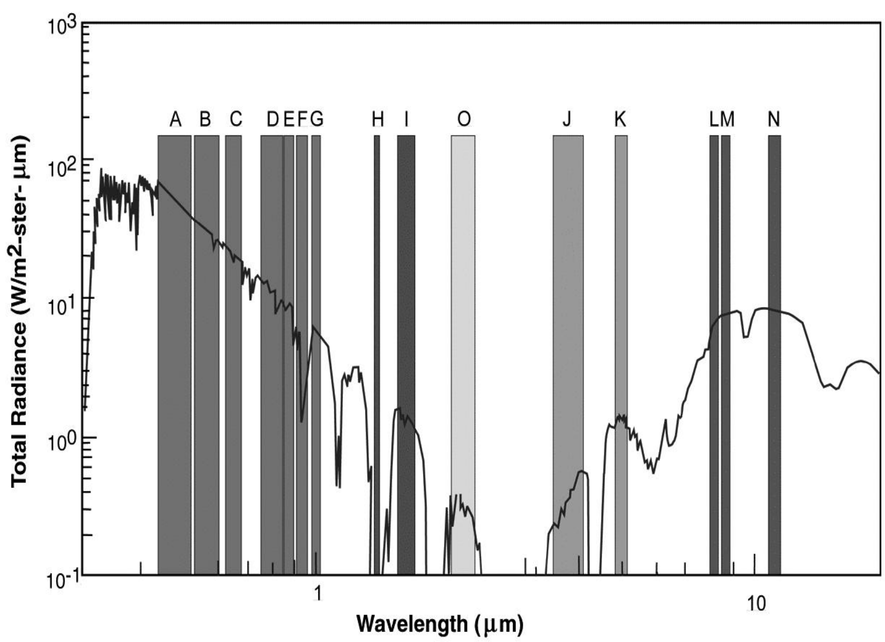

Fig. 2.: Computed spectrum at the MTI payload, with selected spectral bands.

Revisit time to the targets is determined from the need to understand seasonal effects, coupled with cloud coverage which will impede imaging a large fraction of the time. Further, since the swath width is relatively modest, we include the ability for the satellite to steer in all three axes, using reaction wheels. The satellite can therefore point to targets within 55 degrees on either side of the satellite track, and from angles separated by at least 50 degrees in the along-track direction thus allowing stereo imaging in a single pass. The stereo imaging allows some determination of 3-D scene attributes, as well as improving atmospheric corrections by allowing two separate observations at different slant angles through the atmosphere. These attributes permit an average revisit time of one week, and quality data (given typical cloud interference) some two dozen times per year.

The selection of spectral bands involved the obvious trade between using the minimum number of bands for the mission, and mission capability. A rather complete discussion of this topic is available[15] so we limit ourselves to a quick summary here.

For nighttime measurements we are restricted to the infrared spectrum in the nominal 3-5 micron (MWIR) and 8-12 micron (LWIR) regions where the atmosphere is highly transmissive. We take our cue from the sea surface temperature (SST) measurements on weather satellites[16] which use the so-called "split window" technique of two bands in the LWIR and one in the MWIR. Limitations on this technique include the fact that the usual 3.5-4.1 micron MWIR band is too heavily contaminated during daylight to be used for SST. Further, atmospheric effects contaminate the usual SST measurements[17,18]. Thus we implement five bands in the MWIR and LWIR: Band N has a relatively clear view through the atmosphere; bands L and M are located at the transition to water vapor absorption; and bands J and K provide two "anchor" points in the MWIR where the Planck Function changes rapidly with temperature. Band K, despite some contamination due to variable atmospheric constituents, should be usable during day and night collections. In addition to using more spectral bands, we specified a two-look maneuver, in which sites are imaged near nadir and also at an angle of 45-55 degrees off-nadir. This yields two atmospheric path lengths, and allows a far superior correction for the atmosphere, provided that the atmosphere is sufficiently uniform.

For daytime measurements the useable spectral regime for MTI extends from the visible through the LWIR. Spectral band selection in the visible and near-infrared (VNIR) benefits strongly from heritage in hyperspectral airborne sensors such as AVIRIS and HYDICE, and from well-established satellite-borne sensors such as Landsat. Thus bands A-D have Landsat heritage, and are used for materials identification, and for the determination of aerosol effects from the Rayleigh scattering. Bands E, F , and G implement the atmospheric water vapor retrieval pioneered using AVIRIS data[13]. Band H implements the detection of Cirrus clouds and high level aerosols, again following the AVIRIS experience. Band I has Landsat heritage, and is sensitive to lignin in vegetation, coupling with visible bands for vegetation stress measurements. Band O is added for leverage on materials identification, and again has heritage in several sensors. More information on the focal plane array is available[20].

The selection of spatial sampling and spectral bands determines the data rate for the system. Since we wish to achieve excellent accuracy, we will use the on-board calibration sources before and after each image of the target scene. Data are recorded in a solid state on-board memory and down-linked several times a day to the Sandia ground station. Data are then transferred to the Los Alamos Data Processing and Analysis Center (DPAC)[21]. Data products at level one processing include: quick look data, co-registered radiance cubes at the sensor, co-registered geolocated radiance cubes, and, optionally, topographically co-registered and geolocated radiance cubes. At level two processing, products include atmospheric water vapor, cloud masks, surface temperatures, surface reflectances, Normalized Difference Vegetation Index, and materials maps. The DPAC will be the standard interface to all users of MTI data.

The MTI orbit is specified as sun-synchronous with a local crossing time of 0100 and 1300 hrs +/- 1 hour. This choice is determined by the desire to have good thermal contrast in our images. Launch is planned for the end of 1999 with an initial insertion altitude of 575 km at a nominal inclination of 97.52 degrees. The satellite has no orbit maintenance capability, so the orbit will decay over time. The mission duration is nominally a year after a two month check-out phase with a designed reliability of 0.9 (assuming a successful launch) at the end of the year. However, the system has no consumables, and has a goal to operate for three years (by which time we expect the orbit altitude to have decayed to approximately 475 – 500 km).

3. SUMMARY

We have presented an overview of the mission for the Multispectral Thermal Imager. The MTI will provide a demonstration of several new capabilities for space-based remote sensing, including atmospheric compensation based on atmospheric data obtained at the same time and with the same spatial resolution as the imagery, and a significant improvement in calibration of space-based optical / IR sensors. We use physics-based end-to-end modeling and analysis to determine the MTI attributes, and we plan to validate this work with data from the satellite instrument. As of this writing (4/99) the payload has left the Los Alamos Radiometric Calibration laboratory[22] to be integrated with the satellite bus. Launch is scheduled for the end of 1999. Many more details on MTI are provided in subsequent papers in these special sessions.

4. ACKNOWLEDGMENTS

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BIOGRAPHICAL INFORMATION

Paul Weber earned a Ph.D. in Physics from the Flinders University of South Australia. He then accepted a research position at Columbia University, where he worked on the equilibrium and stability of plasmas at high pressures. Since 1980 he has been at Los Alamos starting in the Advanced Diagnostics Group where he developed several particle beam, laser and spectroscopic systems. In 1986 he assumed responsibility for the experimental Reversed Field Pinch Physics program. In 1991 he moved to the Space Science and Technology Division, where he initiated several programs in optical and infrared remote sensing. Paul now leads the Space and Remote Sensing Sciences Group, and continues as Project Leader for the Los Alamos part of the Multispectral Thermal Imager. He is the author, or co-author, of over 170 publications, conference papers and reports.

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